Conceptual Design of a Europa Lander Mission[1]

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Abstract—A Europa Lander mission has been assigned high priority for the post-2005 time frame in NASA's Space Science Enterprise Strategic Plan. Its primary scientific goals are to characterize the surface material from a recent outflow and look for evidence of pre-biotic and possibly biotic chemistry. The mission concept involves landing a single spacecraft on the surface of Europa with the capability to acquire samples of material from 1 meter below the surface, perform detailed chemical analysis of the samples, and transmit the results directly to Earth. Because of the large velocity change required (4 km/sec), the propulsion system comprises over 85% of the 1000 kg launch mass. The spacecraft will require novel, lightweight, radiation-tolerant components; new devices for acquiring, distributing, and processing surface material; miniaturized organic chemistry instruments; and capability to perform an autonomous precision landing on Europa's hazardous surface.

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1. INTRODUCTION

In cooperation with NASA's Solar System Exploration Subcommittee (SSES) the Jet Propulsion Laboratory (JPL) is conducting a series of studies to assess the feasibility of planetary science missions proposed for launch in the 2006-2010 time frame and to prioritize technology development steps that will enable these missions. This paper describes the results of one of these studies, dealing with a concept for a Europa Lander mission. Included are discussions of the science objectives, the major design trade-offs in planning a mission to satisfy these objectives, the resulting mission concept, and identification of technology developments needed to enable the mission.

Europa is one of the most scientifically interesting objects in the solar system because of the strong possibility that a liquid water ocean warmed by tidal heating exists underneath its ice-covered surface. If a subsurface ocean exists on Europa, it can be assumed to contain both organic molecules and heat sources from tidal effects, the decay of radioactive elements, and geophysical mechanisms. Europa's subsurface ocean environment may be similar to that of the deep ocean hydrothermal vents on Earth where life has recently been detected. If life exists (or existed) on Europa, it may pervade the liquid portions of the planet and perhaps be detectable in the dark fracture-filling material from recent ocean outflows on the planetary surface. The possibility of finding traces of biotic or pre-biotic materials has led to a high ranking for a Europa Lander mission among the candidates in NASA's Space Science Enterprise Strategic Plan.

2. SCIENCE OBJECTIVES AND MEASUREMENTS

The top level Europa Lander science objectives are :

(1) Go to one or more surface sites with access to "pristine" (as recently erupted or exposed to the surface as possible) material from an ocean, or other subsurface liquid water.

(2) Characterize the surface composition, especially the organic chemistry, at depths below the critical radiation processing depth (> 0.5 m).

(3) Search for indications of biology.

(4) Determine the global and regional context for the site.

(5) Determine the local thickness of the ice.

The following paragraphs expand these into a set of scientific goals and a list of instruments which can address each goal. Table 1 summarizes this instrument set and describes corresponding current technology status and future technology potential.

Characterization of Liquid Ocean Including Isotopic and Elemental Composition

Important measurements include isotopic and elemental composition of ice, melting point of ice, properties of melted ice including pH, redox potential, conductivity, ionic concentrations, and evolved gas concentrations as a function of temperature.

Possible instruments include wet-chemistry station; electronic nose; electronic tongue; tunable diode lasers; quadruple or magnetic sector mass spectrometer; alpha proton X-ray spectrometer.

Sample handling requires a drilling and coring device for obtaining ice cores. No sample purification or concentration is required, but the wet-chemistry station and electronic tongue will require a sample chamber with a vacuum seal in order to create a liquid melt in Europa's high-vacuum environment.

Presence and Characterization of Pre-Biotic and/or Biotic Compounds

Important measurements include determination of the organic molecular composition of ice on Europa and search for bio-signatures including amino acid chirality measurement and fatty acid analysis.

Possible instruments include gas chromatograph coupled to time-of-flight mass spectrometer; IR and/or Raman spectrometer; UV-visible spectrometer; microfluidic separation system coupled to capillary electrophoresis device for amino acid analysis; microfluidic separation system coupled to liquid chromatograph for fatty acid analysis.

Sample handling requires a device for obtaining ice cores. In order to increase the likelihood of detecting organic molecules, sample purification and concentration will be required using a membrane device and/or some kind of microfluidic system.

Table 1. Instrument Summary

Science goal	Instrument	1998 technology	2004-2007 technology
Characterization of liquid ocean	Wet chemistry laboratory	Simple chemical and pH sensors; ion specific electrodes	Sophisticated chemical sensors; electronic nose and tongue
Isotopic analysis of C, O, other targeted elements in ice	Tunable diode lasers (TDLs)	Some TDLs developed for H_2O sensing, etc.	Array of miniature TDLs targeting wide range of evolved gases
Isotopic/ elemental/ molecular analysis of materials present in ice	Mass spectrometer (MS) or coupled gas chromatograph (GC/MS)	Quadrupole MS: mass ~1.3 kg; power ~15–50 W; mass resolution ~0.5 amu	Coupled GC/MS system with mass <1 kg; power ~1–2 W; mass resolution ~0.001 amu
Presence of bio-signatures	Capillary electrophoresis (CE) device capable of determining amino acid chirality	no CE device developed for in situ exploration	Miniature microfluidic sample extraction system coupled to CE device: mass ~0.8 kg; power ~1–3 W
Presence and characterization of pre-biotic and biotic compounds	UV–visible–near-IR spectrometer	No UV–visible–near-IR spectrometer developed for in-situ exploration	Miniature, low-power spectrometer
Presence and characterization of pre-biotic and biotic compounds	Mid-IR/Raman spectrometer	Raman spectrometer: mass ~2 kg; power ~5 W; delicate and non-rad-hard	Novel TDL-based Raman spectrometer with mass ~0.1 kg; power ~0.5 W; rugged and rad-hard
Imaging and characterization of large particles or particulates	Microscope	Simple optical microscope	Miniature instrument combining XRD XRF optical microscope. Miniature scanning electron microscope combined with X-ray analysis
Imaging of local environment	Active pixel sensor (APS) cameras	Non-rad-hard APS cameras	Rad-hard APS cameras

Imaging and Characterization of Large Particles or Particulates

Important measurements include imaging and possible mineralogical information. Possible instruments include optical microscope, scanning electron microscope (SEM), X-ray diffraction/X-ray fluorescence device.

Sample handling requires a drilling and coring device for obtaining ice cores unless samples are imaged directly on the surface. Instruments will probably examine ice, use a heating device to sublimate all water from the sample, and then examine the remaining material.

Imaging of Local Environment

It may be desirable to mount the imaging camera on a mast which can take pictures covering a 360° field-of-view.

3. Mission Design

This study assumes a launch in the 2007-2009 time frame. The original specification was for a direct transfer to Jupiter, but the energy requirements of this mission made performance too much of a challenge for that minimum time transfer. Instead, a launch to a C_3 of 35 km^2/sec^2 followed by a triple Venus gravity assist trajectory was selected. This has the undesirable effect of increasing the Earth-Jupiter trip time from 3 to 6.5 years. Shortening this time will be the objective of future studies.

The mission design minimizes the propulsion energy requirement to arrive in orbit at Europa by doing a satellite tour after braking into orbit at Jupiter. This will crank the orbit energy down as close to Europa's as possible using gravity assist combined with propulsive maneuvers. A Ganymede flyby as the spacecraft approaches Jupiter reduces the energy needed for the Jupiter orbit insertion and perijove raise maneuvers, which result in about a 200-day orbit.

There follows a sequence of outer Galilean satellite flybys augmented by propulsive maneuvers to reduce the energy of the orbit until it is inside Ganymede's orbit. Then, a series of reverse Europa flybys pump the orbit down to a 6:5 resonance with the target satellite. Europa orbit insertion burn follows, with the spacecraft ending up in a 100-km orbit around the satellite, ready for the descent burn to the surface at a location chosen based on images obtained in previous missions. The spacecraft velocity changes for arrival at Jupiter, satellite touring, and Europa orbit and descent are shown in Table 2.

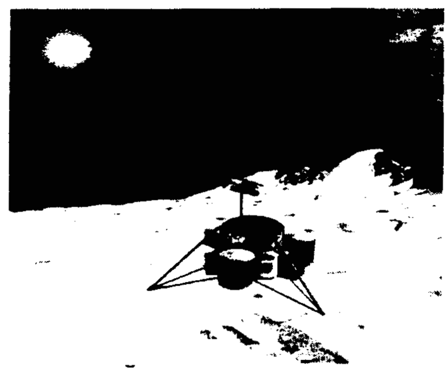
For the selected option and the spacecraft mass given below the required launch uses an Atlas IIAR, for which we assume a 10% launch vehicle performance margin. In the absence of more detailed performance curves, this is assumed to be equivalent to an Atlas IIAS with a 5% margin (the IIAR is planned to be a 5% performance improvement with a significant cost reduction).

The landed mission covers three rotations of Europa, at 3.5 days each, for a total encounter duration of 10.5 days. In these 10.5 days, the instrument suite will collect a total of 145 Mb of data, assumed to be distributed roughly uniformly in time. Europa will be in view of the Earth roughly 24 hr every rotation, so a minimum acceptable data rate to Earth is 0.52 kbps.

Table 2: Breakdown of Spacecraft Velocity Changes

Mission Event	ΔV (m/s)
Jupiter Orbit Insertion/Perijove Raise	750
Europa/Callisto Tour	310
Europa Tour and Orbit Insertion	350
Descent to surface	2200
Margin for g-loss (10%)	360
Total ΔV	3970

4. Spacecraft Systems



A dominating factor in the design of a Europa Lander spacecraft is the radiation environment where the lander is expected to operate. The study estimated a 2 Mrad total dosage to the end of the mission. The system design is based on the planned third delivery from the Deep Space Systems Technology (X2000) Program. This program has been established to develop new technology for deep space missions and to deliver prototypes of flight qualified systems and subsystems incorporating the technology. The third X2000 delivery, scheduled for 2006, will include very light weight radiation-hard avionics. The radiation hardening is expected to be at about 1 Mrad at the component level, so that some shielding will be required for most components. A few components (e.g., gyros) will not be rad hard and will require substantial shielding.

Table 3. Spacecraft Mass and Power

	Mass (kg)	Power (W) Transmit Mode
Payload		
Drill	6	
Instruments	8	8
Bus		
Attitude Control	18	15
Command & Data	2	8
Power	15	9
Propulsion	58	1
Structure	91	0
Spacecraft Adapter	14	
Cabling	9	
Telecom	6	27
Thermal	20	17
Bus Total	246	76
Spacecraft Total (Dry)	260	76
Mass/Power Contingency	78	23
Spacecraft with Contingency	338	99
Propellant & Pressurant	639	
Spacecraft Total (Wet)	977	
Atlas IIAS Launch Capability	1279	

A high level of redundancy was used throughout the design because of the long duration of the mission. Mass and power estimates for the spacecraft systems are shown in Table 3 and a sketch of the lander on the Europa surface is provided in Figure 1.

Propulsion

The total _V required for the mission is 4300 m/s, with about 2000 m/s required to get from the final orbit to the surface of Europa. A two-stage propulsion system was found to save over 200 kg/m launch mass relative to a comparable single stage system. Both Stages have a dual-mode system, with a single, two-axis, gimbalable 450-N hydrazine/nitrogen tetroxide engine, and twelve hydrazine thrusters for roll control during _V maneuvers and for attitude control functions.

Based on current and projected performance expectations for dual mode engines, a reasonable specific impulse for this time-frame would be 330 s, with an aggressive goal of maybe 335 s using rhenium chambers and greater expansion ratios. Since the payload mass difference between 330 and 335 s was relatively minor, the 330 s was baselined for the study, consistent with the current projections for engines under development. Other than differences in the tankage sizes, the two stages were basically identical in design. The primary non-tankage hardware difference was that Stage 1 used 0.9-N thrusters, while Stage 2, 4.5-N thrusters. Both stages used composite tanks for propellant and pressurant. Stage 1 was sized assuming 2300 m/s and would be separated just prior to deorbit, leaving the remaining 2,000 m/s for Stage 2 to perform.

Attitude and Articulation Control

The attitude and articulation control system (AACS) provides four major functions: attitude determination, attitude control, landing guidance and control (G&C), and articulation control for the main engine and the high gain antenna (HGA). The AACS design relies heavily on heritage from X2000, but it also requires development of new landing techniques and subsystems. A functional block diagram of the AACS is shown in Figure 2. Key requirements include pointing the HGA to within thirty arc sec of the estimated Earth position and landing within 1 km of the targeted location. It is assumed a 10 m resolution map of the target area will be provided by a previous mission (Europa Orbiter planned for launch in 2003).

Attitude Determination—The attitude determination system will consist of fine sun sensors which will be co-boresighted with the HGA for initial acquisition and HGA pointing knowledge, APS star cameras which will provide the spacecraft three-axis fine pointing knowledge, and micro-IMU's in multi-chip module (MCM) format with 0.1°/hr bias stability used to propagate attitude rates when

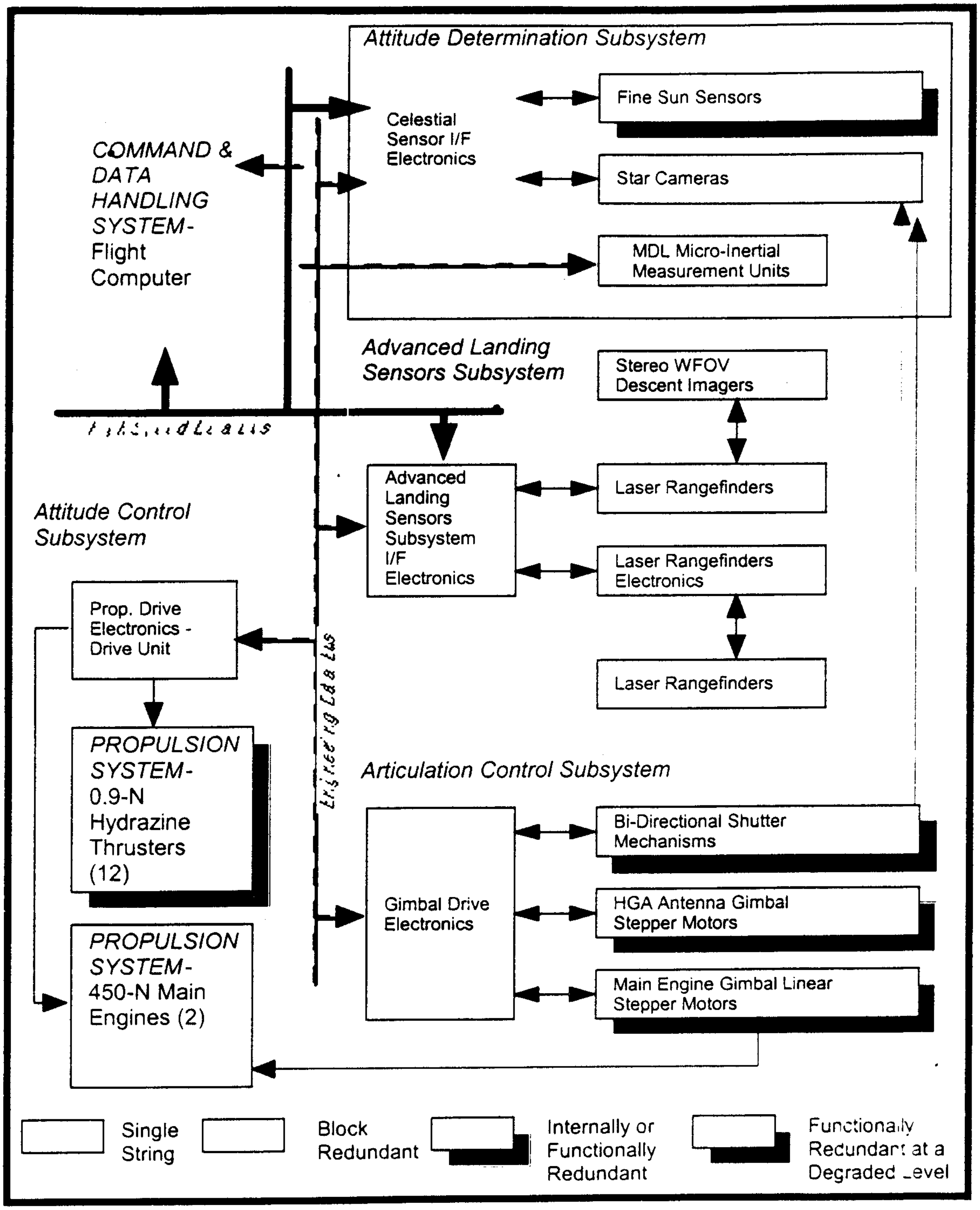


Figure 2: Functional Block Diagram of Europa Lander AACS

the star cameras cannot be used (during attitude maneuvers, main engine burns, etc.) Each star camera will have a bi-directional 400-mil thick aluminum shutter. When the Europa Lander is in a high-radiation environment, these shutters will remain closed except when the gyros need to be updated. The AACS will provide the gimbal-drive electronics and controllers as well as the valve-drive electronics and controllers for the attitude control thrusters. Trades performed in a prior Europa Lander study have shown that reaction wheels are not required with the present set of mission requirements.

Landing G&C—Autonomous guidance and control for descent and landing requires six degree-of-freedom (DOF) thrust-vector control (TVC) and maneuver capabilities to enable a safe, precision soft landing. The capabilities include autonomous trajectory path guidance and hazard avoidance during descent to the irregular/chaotic ice fields of Europa. Requirements on the Europa Lander G&C system will include the following functional capabilities:

- Two-body descent and maneuver dynamics and stability envelope prediction.
- Descent guidance laser rangefinder and stereo imaging system, using APS focal-plane technology, with autofocus and autostabilization over a >1000:1 dynamic range in descent from the 100-km orbit to a horizontal maneuvering altitude of under 100 m .
- Terrain correlation tracking during descent for target landing site recognition .
- Target-relative closed-loop terminal-path guidance laws .
- Lander TVC algorithms for adaptable glide slope and heading control in path guidance and maneuvering.
- Soft-landing approach lateral and/or hovering maneuvers using visual observation to avoid hazards and land in a preferred touchdown site.
- Gimbaled main engine with an articulation range of $\pm 30^\circ$ in two axes.

Landing guidance provided by the advanced landing sensors subsystem (ALSS) which will consist of a dual redundant WFOV stereo descent imager and laser rangefinder system. This system will be used with the IMU to meet the precision landing guidance and navigation requirements. The ALSS optical sensors will remain covered with 400 mils of Al shields until pre-landing operations at which time these covers will be removed.

Articulation Control—Articulation control for the 450-N main engines with linear actuators will be similar to those used by the Cassini engines of the same size. Articulation of the HGA will be provided by two rotary stepper motors with _0.002° resolution to meet the HGA pointing control requirement.

Command and Data Handling

This system also relies heavily on the miniaturized radiation tolerant avionics planned for X2000 third delivery. The command and data system (CDS) consists of two identical units operating in a string A and string B fashion and will perform the following functions:

- Uplink command processing and distribution.
- Sequence storage and control.
- Maintenance and distribution spacecraft time.
- Collection and formatting of engineering spacecraft sensor data.
- Bulk storage of science and engineering data.
- Subsystem control and services.
- Spacecraft system control services
- Science data processing
- Spacecraft fault protection.
- Reed-Solomon downlink.

CDS will collect 265 Mb of science and spacecraft engineering data during the 10.5-day period and will perform 2:1 lossy data-compress algorithms on the science data. These reduce the total volume to 145 Mb. Packetization and encoding overhead will increase the overall downlink data volume slightly.

Each CDS string will have three MCMs weighing 1.0 kg per string inside a 200-mil aluminum enclosure. The estimated radiation dose inside the enclosure is 1 Mrad. Detailed functionality will include the following:

- PowerPC 750 Processor: 250-MIPS processing will include spacecraft commands and science data compression. The processor module provides the Telecom data formatting for Case 3. Power strobe controls will power down MCMs when they are not in use. MCMs that are powered off will be less susceptible to the effects to the TID environment.

- I^2C Serial I/O Bus—I^2C bus will communicate with science instruments and spacecraft subsystems. Science data and controls will transfer over the redundant bus at 100 kbps.

- RFS Uplink/Downlink—The interface link to the Telecom Subsystem will process uplink data at 2 kbps and downlink science and engineering data 1 kbps.

- Flash NV Memory—power strobes the Flash NV Memory will be powered off when not in use to increase the reliability of the devices regarding the TID environment.

- Mbps FireWire I/F—High-speed data from the star camera will be capture with a 100 Mbps FireWire interface.

- 60K - 230K Gate Array—The FPGA with high speed data control for the star tracker.

Power

The power subsystem drivers are the mass of the power generation component and the mass for shielding of electronic components. For the power generation, we have assumed judicious advances in radioisotope power generation. A simple trade revealed that significant mass could be saved by using a secondary battery to level the mission power modes (sized for descent and landing).

Power Generation—The major component of the power subsystem for this mission is an advanced radioisotope power source (ARPS). The ARPS is based on the 21 % efficient AMTEC (alkali-metal thermoelectric converter) using a two-brick GPHS (general purpose heat source) currently under development in the X2000 program. This power generator is expected to deliver 96 W at the end of a 12-yr mission. The generator has a predicted mass of 10 kg.

Power Storage—Energy storage for this mission will be provided by a secondary lithium-polymer battery. The battery was sized to load-level the descent and landing mode. The battery will provide the remainder of the power not provided by the ARPS during the 1-hr descent and landing including the energy required during 2 minutes of propulsion burns during this mode. The total energy required is 146 Whr which will be provided by two lithium-polymer 6-Ahr batteries weighing 1.5 kg each.

Power Electronics — Power switching, management, and distribution assumes X-2000–3 delivery MCM technology. This technology is expected to dissipate 250 W/kg; thus the total mass of the power electronics is expected to be 2.4 kg.

Thermal Control

The thermal control system will include a thermal distribution system which takes advantage of the waste heat that is normally rejected by the AMTEC. This is key to keeping film-heater electrical power down to a manageable level both for cruise and landed operations. The staged propulsion units will require a segmented thermal distribution system which would accommodate both cruise and landed modes. The distribution system is a capillary, pumped-type loop which is capable of high heat transfer in a minimum diameter size line.

For landed operations, an IR shield is employed to minimize AMTEC/site radiant heating interactions. If this were not the case, it is conceivable that the lander-anchor integrity could be compromised by the 300 °C (573 K) case temperature on the AMTEC. The physical configuration of the IR shield would be a multistaged V-groove design to successively stage the temperatures down from 300 °C to levels of temperature consistent with maintaining the site-anchor integrity.

Local thermal control is provided by a set of film heaters, thermostats, and sensors for the propulsion system and key electronics subsystems. Total power requirements are about 17 W in landed operations and about 9 W in cruise for the baseline 2007 system.

Structures

The structure mass was estimated parametrically based on the masses of the other subsystems which the structure supports, plus specific substructures, components, and mechanisms. While structural materials and concepts are not a quickly progressing field, assumptions consistent with the projected technology level were used for the mass estimates. Technology assumptions for structures and cabling include:

- Advanced non-metallic composites providing ~15% mass saving over current technology.
- Use of MFS (multi-functional structure) in electronics bus; this integrates structure, electronics housings, cabling, and some inter-unit connectors.

Telecommunications

The mission will have three communications phases: the launch phase, the cruise phase and the encounter phase. The encounter phase (after landing on the surface of the moon) will last about 1 to 2 months.

Encounter Mode Communication—The range between the spacecraft and DSN at the encounter will be assumed to be about 4.3 AU. The range will remain 4.3 AU for the orbit around Europa as well as the landing phase. Ka-band frequency will be used for the telecommunications operations. During the encounter, the DSN 70-m antenna will be used to receive the telemetry. The 70-m station will be assumed to have the Ka-band receive capability by the time the mission launches. The encounter will last only about one month or so.

The bit rate will be 1 kbps. The telemetry transfer frame will be produced in accordance with the CCSDS format. The data will be directly modulated on the carrier. The telemetry link will use the rate 1/6 constraint length 15 convolutional coding concatenated with the JPL standard 223/255 Reed-Solomon block code. This arrangement will have a requirement of bit-energy-to-noise density ratio of about 0.8 dB. The link will have a data margin of 3.0 dB and the carrier margin of 6 dB. The total loss of the spacecraft telecommunications system is limited to about 6 dB.

The telecommunications link will use a parabolic reflector high-gain antenna (HGA) of about 0.35 m diameter. This will have a gain of about 38 dB and will have a 3 dB end-to-end beamwidth of about 1.7°. The antenna will be pointed by the attitude control system (ACS) and hence the telecom system will not carry the gimbals. The pointing accuracy necessary will be about 0.16° to limit the antenna pointing loss to about 0.1 dB. The radiated power of 5 W (RF) will sustain the link. The ground station receiver (Block V receiver) will have a threshold of 12 dB and the carrier tracking loop expanded bandwidth to be no larger than 10 Hz.

Cruise Mode Communications—The cruise mode communications will begin once the journey to the target begins. This does not include the launch mode. The cruise mode communications will use the spacecraft's 0.35 m diameter parabolic reflector HGA. The link will support a bit rate of about 0.15 kbps. The data will be coded using the same rate 1/6 constraint length 15 convolutional code concatenated with the JPL standard 223/256 Reed-Solomon block code. The RF radiated power will be same as before, 5 W.

The cruise mode lasts up to the encounter, consequently making the worst case range of about 4.3 AU. The cruise mode communications will be used to downlink the spacecraft's health status consisting of the payload health and the subsystems health data. The data will be downlinked to the DSN 34-m beam waveguide (BWG) station with only a few contacts with the ground station (such as two times a week).

This link will provide a carrier margin of about 6 dB and a data margin of about 3 dB. The radiated power is 5 W RF and the total losses of the link are limited to about 6 dB as before. The receiver on the ground (Block V receiver) will be assumed to have an expanded carrier tracking loop bandwidth of about 5 Hz.

Emergency Mode Communications—When an emergency develops on the spacecraft, the 70-m ground station will be used to establish the link. The bit rate will be reduced to about 5 bps. The link will use a low/medium gain antenna of about 5 cm diameter. The data will be riding on a subcarrier to avoid the interference with the carrier tracking loop. The data will use the same coding as before to provide a low required bit energy to noise density ratio. The ground station receiver (Block V receiver) will have the carrier loop expanded bandwidth of 1 Hz. This assumes that the Doppler on the spacecraft is known and can be biased out at the carrier tracking loop. The data margin is about 3 dB. This link allows a total loss about 6 dB.

Programmatics

The launch approval process for this mission is a real issue because of the ARPS. That process requires that a data book be available that describes the power system and both the launch vehicle and the spacecraft. This is used for a thorough analysis of possible failure modes and probabilities. By the year 2007 we can assume that the AMTEC RPS will have been described, tested, and analyzed. There is now a concerted effort going on to get it approved for space flight. The Atlas IIAR launch vehicle is, however, problematical. There are now no specific plans to generate a data book for it and the addition of the Star 48 upper stage complicates the issue. The work to generate the required data is estimated to take at least two years. It is therefore a pre-Phase A cost and some arrangement for its funding outside the normal project funding must be made.

5. Cost

Mission end-to-end costs were estimated using the Team X to Develop New Products (DNP) cost model. This is based on mission implementation using the JPL DNP process which includes the use of behavioral and cross-cutting models, test bed development, and art-to-part. The model is used by subsystem designers to generate cost estimates for their hardware, software, and operations which they can adjust based on the specific characteristics of the mission. The subsystem estimates are then used by the cost analyst in another part of the model which applies DNP-based overhead estimates to generate the overall cost. The project development cost estimate (phases A, B, C/D) is summarized in Table 4. These costs are based on the 33-month development life cycle planned for JPL projects launching in the middle of the next decade. Table 5 lists the Mission Operations (Phase E) costs and the total mission costs.

Table 4. Phase A, B, C/D Cost Summary in FY '98$M

Project Management	7.2
Outreach	1.4
Launch Approval	5.0
Project and Mission Engineering	14.3
Payload	24.7
Instrument Support	3.5
Spacecraft	84.3
ATLO	7.1
Science	3.6
Mission Operations	7.5
A, B, C/D Sub total without LV	158.6
Reserves at 20%	31.7
Launch Vehicle	105.0
A, B, C/D total with LV and reserves	295

Table 5. Phase E and Overall Mission Cost Summary in FY '98$M

Project Management	4.2
Science	3.5
Mission Operations	29.0
Phase E Subtotal	36.7
Reserves at 10 %	3.7
Phase E Total	40
Phases A, B, C/D Total	295
Mission Total (Phases A through E)	335

6. TECHNOLOGY NEEDS

Many technology advances are needed to enable useful science return from a landed mission on Europa. The spacecraft will require novel, lightweight, radiation-tolerant components and, in the current landing scenario, must be able to perform an autonomous precision landing on Europa's surface while avoiding poorly defined hazards. Current work on advanced radioisotope power sources must be successfully completed. New technologies are also necessary for the miniaturized instruments which will perform the desired scientific investigations.

Radiation-Tolerant Components

All of the avionics and instruments on the proposed Europa Lander will require radiation-hard electronics. The capability to survive a total ionizing dose (TID) of ~1 Mrad or greater was assumed in estimating shielding mass. Techniques for fabricating radiation-hard micro-processors and A/D converters include using CMOS processes, silicon-on-insulator, or silicon-on-sapphire processes, and using bipolar transistors. The availability of extremely radiation-hard space-qualified electronics is perhaps the most critical technology requirement for enabling future Europa missions.

In addition to radiation-hard electronics, other instrument components (i.e. optical fibers, optical detectors, charged-particle detectors) must be designed or modified to survive in Europa's harsh radiation environment without the need for massive radiation shielding. In particular, the optical detectors currently used by active pixel sensor (APS) cameras are extremely sensitive to radiation. An extremely useful technology development for future Europa missions is the development of radiation-hard APS cameras using CMOS processes or similar radiation-hard processes. Ideally, all components of the instrument package will be radiation tolerant to at least 100 krad levels so that the required radiation shielding is not prohibitively massive. The importance of developing radiation-hard components can be illustrated by the following example. The total mass allotment for the landed instrument package is expected to be ~10 kg. If the radiation sensitive components are radiation-hard to only 10 krad and can be contained in a small 10- ×10- × 10-cm science box, the required aluminum shielding will have a prohibitively large mass of ~100 kg.

Devices for Acquiring, Distributing, and Processing Surface Material

The specific sample-handling strategies will depend on the instruments, but at least four types of general sample handling devices are likely to be needed by the proposed Europa Lander mission: (1) a drilling and coring device for acquiring ice samples at depths of up to a meter below the surface; (2) a sample distribution device to supply the various instruments with material; (3) a vacuum-sealable chamber for melting water-ice in Europa's high vacuum environment; and (4) sample purification and concentration systems consisting of membrane and/or microfluidic devices.

In general, these sample-handling devices are more developed than the scientific instruments described below and are expected to be available sooner. An important exception is the miniature microfluidic system for extracting amino acids, fatty acids, and other molecules of biological interest from the Europan ice. Autonomous microfluidic systems are in the earliest stages of development and will require the most investment to achieve flight-readiness.

Lightweight, Low-Power Instruments

Important technology developments for Europa Lander instruments can be divided into two categories: first, reducing the mass and power requirements of existing instruments while increasing or maintaining the science return; and second, developing entirely new instruments to study pre-biotic and biotic chemistry.

For instruments in the first category, the required technology developments are for the most part instrument-specific. For example, a miniature quadruple mass spectrometer for in-situ studies currently has a mass of ~2 kg of which ~100 g is required for the mass analyzer. The instrument mass is dominated by the required high-frequency, high-voltage electronics, and therefore technology developments which lead to reductions in the electronics subsystem mass are more critical than developments which lead to further miniaturization of the mass analyzer. As a second example, in order to significantly reduce the mass of a miniature Raman spectrometer from 2 kg to less than 0.5 kg, technology investments in low-mass, low-power UV and blue lasers will probably be required.

Some of the proposed science goals for a Europa Lander cannot be addressed with existing instruments. In particular, many instruments for studying pre-biotic and biotic chemistry are either at the earliest stages of technological development or are not yet being developed for in-situ exploration. Among these are a miniature portable UV–visible–near-IR spectrometer from 200 nm to 5000 nm, a capillary electrophoresis device to study the chirality of amino acids (dominance of either chirality would be an unambiguous bio-signature), and a device to study the number of carbon atoms in fatty acids (more even-chain than odd-chain fatty acids would be an indicator of life).

Autonomous Landing and Hazard Avoidance

The surface of Europa has been described as being "rough at all scales". Images from precursor missions will be used to establish the desired landing zones but will not identify hazards at the scale of the lander, so the lander must be extremely robust or must be able to avoid large surface irregularities (autonomously due to the long light time).

Propulsion Technologies

Table 2 shows that propulsion systems account for more than 80 percent of the launch mass so propulsion technology advances can have a significant payload impact. This includes both specific impulse increases and component mass reductions. Although not covered in this study, advances in low thrust propulsion technology (solar electric or solar sail) have been found in other studies to be potentially beneficial to a Europa mission.

Power

A high performance radioisotope based power source is crucial to the Europa Lander concept. Such a system is being developed by the Advanced Deep Space Systems program and its successful completion is important to several planned outer planets missions.

7. CONCLUSIONS

A Europa Lander mission satisfying the objectives of the SSES could be feasible for launch in the 2007 timeframe with appropriate investment in the technology areas described in the previous section.

8. ACKNOWLEDGMENTS

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